Energy and Buildings 141 (2017) 142–157

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Old and cold? Findings on the determinants of indoor temperatures in English dwellings during cold conditions

I.G. Hamilton*, A. O'Sullivan, G. Huebner, T. Oreszczyn, D. Shipworth, A. Summerfield, M. Davies

UCL Energy Institute, University College London, UK

ARTICLE INFO

Article history:
Received 2 October 2016
Received in revised form 25 January 2017
Accepted 6 February 2017
Available online 13 February 2017

Keywords:
Indoor temperature
Cold
England
Energy performance
Dwellings
Households

ABSTRACT

Indoor temperatures during winter conditions play an important role in influencing the comfort and health of households, space heating energy demand and peak heating power. The role that physical dwelling features and household characteristics have on wintertime indoor temperatures has been examined among low-income households, but not across English households in a systematic manner. This paper examines determinants of indoor air temperatures during wintertime conditions to examine how temperature conditions vary with, for example, dwelling age or household socio-economic conditions. Using a cross-sectional survey of English dwellings that included monitoring of indoor air temperatures from January 2011 to February 2012, this study examines the determinants of indoor temperatures during wintertime conditions within a representative sample of English dwellings (N = 821). The study analysed indoor temperatures standardised to outdoor air temperatures of 0 °C, 5 °C and 10 °C within the study sample and the influence of physical dwelling features (type, age, size), household characteristics (tenure, income, composition, benefit receipt) and energy performance (loft and wall insulation, heating system and performance rating levels). The analysis finds that as dwelling age decreased (i.e. newer), so did indoor air temperatures in both the living room and bedrooms, after adjusting for a selection of dwelling and household characteristics. Compared to the lowest income quintile, households with higher incomes kept warmer temperatures, but this was not a linear increase and the highest incomes were not on average the warmest. There appears, however, to be little change in the dwelling temperature trends when looking at lower or higher outdoor air temperature conditions (i.e. 0 °C and 10 °C). In designing policies to improve indoor thermal conditions, policymakers will need to consider underlying energy performance of the dwelling alongside the socio-economic conditions of the household, for example when providing fuel support payments to at risk households.

© 2017 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Exposure to wintertime indoor temperatures remains an important determinant of health for English households. Exposure to low indoor wintertime temperatures is associated with being in fuel poverty and poverty more generally [1,2], and a higher risk of cardio-respiratory illness [3]. England has a large burden of excess winter mortality (EWM), i.e. number of deaths during winter periods (i.e. December to March) compared to the mean of non-winter period, with approximately 18,200 additional deaths in 2013/14 (and 31,280 in 2012/13), and most of this burden is due to deaths attributable to circulatory and respiratory disease (63% in 2011/12) [4]. EWM is above average in England and Wales compared to much of Europe, which is a trend exhibited among other countries with milder winter weather [5]. EWM has been attributed to inadequate protection from cold temperatures which can be related to: inadequate clothing, poor dwelling thermal efficiency, and low indoor temperatures (i.e. <18 °C) [6]. Exposure to low indoor temperatures has been associated with higher rates of EWM from cardiovascular disease in England [7] and may be attributable for 9% of the risk for high blood pressure in Scotland. In addition to the implications for health, indoor temperature demand is an important driver of space heating demand, which is estimated to account for 54% of the annual average dwelling energy demand in England [9].

The risks associated with living in cold homes and the implications for health and wellbeing more broadly make understanding the determinants of indoor exposure to cold an important area

* Corresponding author at: UCL Energy Institute, University College London, Central House, 14 Upper Woburn Place, London, WC1H 0NN, UK.
E-mail address: i.hamilton@ucl.ac.uk (I.G. Hamilton).

http://dx.doi.org/10.1016/j.enbuild.2017.02.014
0378-7788/© 2017 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

for policy action. Therefore, the objective of this study is to determine the variation in wintertime indoor temperatures associated with dwelling features, household characteristics, and measures of energy performance. A further objective is to determine how wintertime indoor temperatures vary with outdoor temperature, with a particular focus on 'cold periods' and outdoor temperature cold thresholds. The research questions asked were:

1. Are older (and presumably less efficient) homes colder than newer homes?
2. Are households of lower levels of socio-economic status colder than those of higher economic status?
3. Do these relationships change during colder periods? and
4. How do retrofits modify the exposure to indoor temperature?

A cross-sectional survey dataset of English dwellings with monitored indoor wintertime temperatures over a 13-month period during 2010 and 2011 was used to investigate the association between household and dwellings characteristics and indoor wintertime temperatures. The temperatures of the homes are standardised to a common external temperature to enable comparison across the sample and with a focus on living room and bedroom temperatures as indicators of likely exposure conditions. In the following section provides a background on past studies conducted in England followed by a description of the data sets and analysis method used to address the research questions.

2. Background

There is a growing interest in better understanding the relationship that indoor thermal conditions have on a range of outcomes, such as heating or cooling energy demand [10,11], levels of activity [12], and of health outcomes such as COPD and cardiovascular disease [13]. Indoor temperatures are influenced by a range of factors, including regional climate, social practices, building energy performance, and fuel prices to name a few. This means that determinants of indoor temperatures will be reflective of local contextual drivers, for example, a recent study of indoor thermal conditions in China found a tendency of very low average indoor wintertime temperatures (e.g. 13 °C) and were influenced by income, presence of children and heating system type [10].

When developing policies on tackling low indoor temperatures for a specific country or region it is vital to understand the prevalence of those conditions and their determinants across the broader population. A recent review of indoor temperature thresholds for health found that few studies had been undertaken at a population level with sufficient coverage and sample size [6]. The objective of this study is to better understand what dwelling and household characteristics influence wintertime indoor temperatures in England, which is marked by high levels of excess winter mortality and also fuel poverty [4,14]. The following studies are included here due to their specific focus on determinants of indoor temperatures among the English household population.

A study by Vadodaria et al. of indoor temperatures samples in England has shown that indoor living room temperatures have broadly stayed the same over the past 40 years, with most samples used to determine this being within the range recommended by WHO (i.e. above 18 °C) [15]. The study also showed that from a limited number of samples, to achieve thermal comfort satisfaction in the UK, living room temperatures may need to be in the range of 20–22 °C. The study was not, however, able to examine determinants of the indoor temperature.

A study by Wilkinson et al. used survey data on English dwellings from the 1991 Energy Follow-Up Survey (EFUS) linked to postcode level mortality data for a ten-year period (1986–1996) to examine the relationship between indoor air temperature and EWM. The EFUS temperature survey took spot air temperature readings outdoors and indoors in the main living rooms and hall/stairs measured in 4942 dwellings between February and May 1992 [16]. In the Wilkinson study, the internal temperatures were standardised to an outdoor air temperature of 5 °C at 3pm after four hours of heating. The standardisation allowed for comparison over time and for different areas of the country. The study found that older (pre-1900) properties had lower wintertime indoor temperatures than post-1980 (-1.20 °C), that dwellings with no central heating were colder (−1.3 °C) than those with, and households in the highest income quartile had higher temperatures (0.25 °C) than those in the lowest. The study also showed that residents living in older and colder homes had a higher risk of excess winter death caused by cardiovascular disease and other causes.

A study by Oreszczyn et al. used a similar method of analysing temperatures as Wilkinson et al. by standardising indoor temperatures to an outdoor air temperature of 5 °C. The study examined temperatures in low income households in England who were recipients of the government Warm Front programme that provided energy efficiency retrofits to tackle fuel poverty. Using the standardised internal temperature for the living room during the daytime (08:00 to 20:00), they showed that among the low income households higher temperatures were associated with newer dwellings (∼0.53 °C), that detached dwellings were colder than terraced dwellings (−0.17 °C) and flats even colder (−0.30 °C). Dwellings with a higher level of efficiency, measured using the notional dwelling fabric heat loss divided by the heating system efficiency, were 1.37 °C warmer than lower levels. Using the government's standard assessment procedure (SAP) the difference between those dwellings in the most efficient bands (>70) were 2.24 °C warmer than those in the lowest (<42). They also found that older (>60) households were warmer (0.52 °C) and those that had difficulty paying their bills were colder (−0.67 °C). The study also included overnight bedroom temperatures, which showed very similar trends as the living rooms. A notable exception was that dwellings with older occupants had lower night-time bedroom temperatures (−0.79 °C).

A study by Kelly et al. examined 347 homes from across England and used a panel approach to examine the determinants of indoor temperatures at 45 min intervals during an ∼6 month period (22 July 2007–3 February 2008) [17]. They found that households with heating controls had lower average daily temperatures compared to no controls (0.24 °C), that homes with more occupants increased their average daily temperature by 0.25 °C/person, that temperature increased with income (0.085 °C/income bracket), that older households (>64 years) had higher temperatures than younger households (0.37 °C), and that socially and privately rented dwellings had higher indoor temperatures than owner-occupiers. Kelly also found that the presence of gas central heating was associated with lower temperatures than those without (−0.56 °C) and those with electric room heating as much warmer (1.0 °C), while the presence of gas and electric room heaters decreased average daily internal temperatures (−1 °C). Dwelling energy efficiency was also shown to be an important determinant of the variation in daily average indoor temperatures, with increased temperatures associated with increased levels of loft insulation (0.25 °C/25 mm), wall insulation (0.08 °C/U-value band), and proportion of double glazing (0.19 °C/25% of glazing). The detachedness of the dwelling (i.e. a proxy for exposed surface area) also affected temperatures, with detached dwellings being colder than semi-detached and terraced dwellings (−0.7 °C and −0.61 °C respectively), while temperatures increased in newer dwellings with post-2003 dwellings being ∼0.42 °C warmer than pre-1900 dwellings.

The above studies of England show that average wintertime indoor air temperatures are influenced by dwelling age, thermal

Table 1
Temperature data exclusions.

	Dataset A: Hourly		Dataset B: Daily	
Temperature logger location	Pre-exclusion	Post-exclusion	Pre-exclusion	Post-exclusion
Living Room	7,613,492	7,235,128	308,796	297,152
Bedroom	7,579,763	7,167,670	310,145	299,850
Hallway	7,564,728	7,137,600	308,525	296,610

Table 2
Summary statistics of mean daily (Dataset A) and hourly (Dataset B) monitored temperatures from EFUS sample (N = 821).

	Summary Statistics											
	Daily temperature (°C)						Hourly temperature (°C)					
Monitoring locations	N	Mean	Std Dev	Median	p5	p95	N	Mean	Std Dev	Median	p5	p95
Outdoor	318,627	10.3	5.1	10.9	1.1	17.5	6,333,945	10.5	5.6	10.8	0.8	19.2
Living room	308,796	19.9	2.6	20.1	15.4	23.7	7,613,492	19.9	2.7	20.1	15.2	24.1
Bedroom	310,145	19.7	2.7	19.8	14.9	23.8	7,579,763	19.7	2.8	19.8	14.7	24.0
Hallway	308,525	19.5	2.7	19.7	14.9	23.5	7,564,728	19.5	2.8	19.7	14.7	23.8
Average [a]	320,427	19.7	2.5	19.8	15.4	23.5	7,988,088	19.7	2.6	19.9	15.2	23.7

Notes: a) Average of living room, bedroom and hallway.

performance, household size and income [7,18]; while dynamic variation in indoor temperature (i.e. throughout the day) is associated with temperature controls, occupancy period, number of occupants, ownership status, heating system type and fabric insulation [17]. However, these studies have not looked at the determinants of indoor temperatures during cold or wintertime periods that are known to have a link to health or were focused on low income and vulnerable populations alone. The Kelly et al. study did not explicitly look at cold or wintertime periods that are known to have a link to health [7] and the Oreszczyn et al. was sampled from fuel poor households and therefore would not represent the broader English household population [18]. The one study that did look at wintertime conditions among a representative sample (i.e. Wilkinson et al. used data that is now almost 25 years old and would not reflect the millions of energy efficiency retrofits that have been installed over the period to present day [19] or changes in thermal comfort and indoor temperature trends [15]. Hence in this study we use an updated dataset of monitored indoor temperatures with comprehensive building measurements to examine determinants during cold wintertime conditions.

3. Methods

This study used data from the 2011 Energy Follow-Up Survey (EFUS), which is a cross-sectional sub-sample survey of households in the English Housing Survey (EHS) 2010–2011, carried out by the Building Research Establishment (BRE) on behalf of the UK Dept. of Energy and Climate Change (DECC). The Survey was conducted through face-to-face interviews with 2616 households between December 2010 and April 2011 [20]. Within a further sub-sample of 823 dwellings, temperatures were monitored in three zones within the dwelling, e.g. living room, hallway and main bedrooms for approximately a year period. This study used the sub-sample of 823 dwellings for the analysis.

The study of temperature and dwelling energy efficiency comprised two main components. The first was the development of an internal temperature standardised at 5 °C outdoor air temperature in order to estimate wintertime conditions and make comparisons between dwellings. A similar method as described in Oreszczyn et al. and Wilkinson et al. was used. The second was to estimate dwelling energy efficiency, also following the method in Oreszczyn et al. The sections below provide a brief description of the temperature data, standardised internal temperature (SIT) model, and the dwelling heat transfer characteristic (i.e. E-value) model. These two components provided a means for analysing differences in temperatures within the survey dwellings under approximately similar outdoor conditions and for characterising the thermal performance of the building.

3.1. EFUS temperature data

The 2011 EFUS installed temperature loggers in 823 dwellings [21]. The loggers recorded temperatures at 20-min intervals in the living room, hallway and main bedroom, where available. The loggers used in the EFUS temperature survey were Tinytag Transit 2 data loggers made by Gemini Data Loggers. The units had a capacity of storing 32,000 readings with an accuracy of ±0.2 °C and a range of −70 °C to 40 °C [21]. The monitoring period was from the beginning of February 2011 to the end of January 2012, capturing a full winter and summer period. Outdoor temperatures were not collected using the temperature loggers during the temperature survey due to 'practical issues', e.g. placement of the loggers and risk of sunlight falling directly on the loggers, instead hourly data from the nearest Met Office weather station system (MIDAS) was used [22]. The MIDAS system comprises 139 weather stations from around England and the majority (75%) of dwellings were within 24 km of a weather station, with the mean being 11 km [21].

For the analysis, 821 dwellings were used (two dwellings were excluded due to errors in the provided datasets) and the 20 min interval logger data for each zone for each dwelling was summarised into a daily temperature (dataset A) and hourly temperature (dataset B) for the monitoring period comprising the mean, minimum, maximum, 5% percentile and 95% percentile values for the living room, bedroom and hallway. For each dwelling, the daily and hourly data points were examined and an exclusion criteria was applied. The exclusion aimed to reduce extreme values or logger errors (i.e. continuous repeats) that could affect the analysis, the criteria was: Repeated temperature values, indoor temperatures <0 °C and >40 °C. This lead to an exclusion of approximately 5% and 4% of the daily and hourly dataset (see Table 1).

3.2. Standardised internal temperature model

The daily and hourly datasets were used to examine the relationship between the indoor and outdoor air temperatures over the monitoring period. This work was mainly focused on examining the indoor temperature exposure during cold (winter time) conditions, which would be equivalent to a 'heating' mode. To compare internal

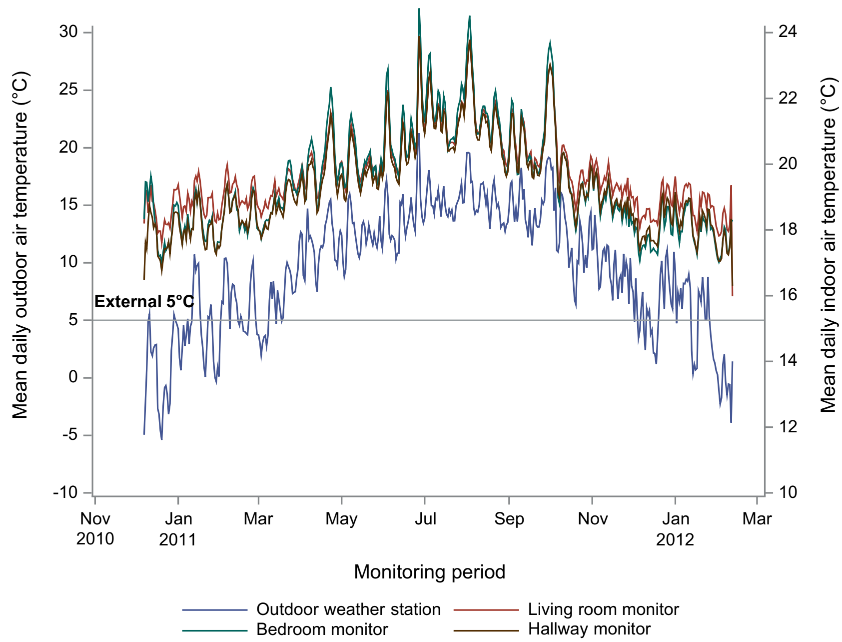

Fig. 1. Daily mean air temperatures for all EFUS monitored dwellings (N = 821).

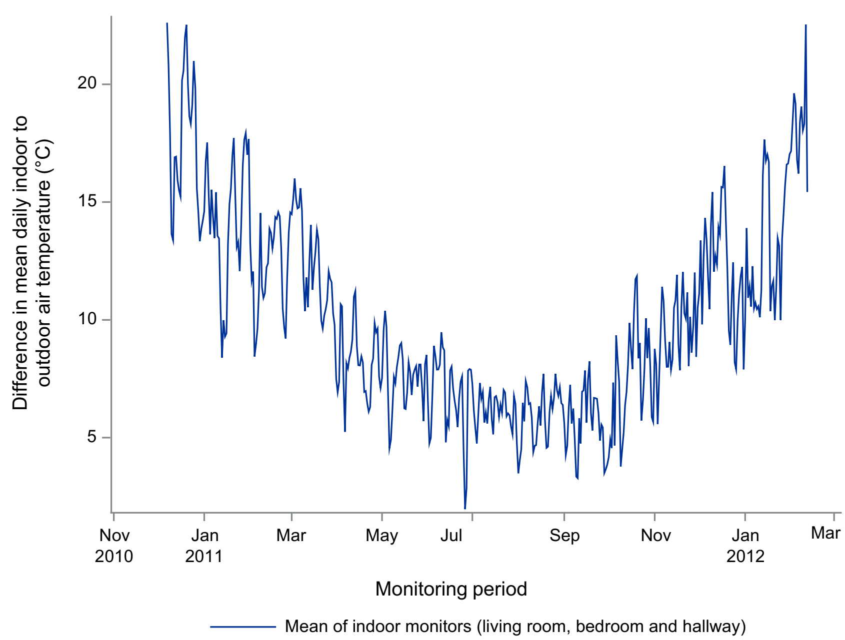

Fig. 2. Daily mean air temperatures for all EFUS monitored dwellings (N = 821).

temperatures between dwellings using monitoring data that was collected across the country and (at times) during different periods it was necessary to create common baseline. The method developed by Oreszczyn et al. to examine the drivers of temperature in low income households provides a useful process of standardising the internal air temperature for a given outdoor air temperature.

This research applied the Oreszcyzn method by using the hourly indoor and outdoor temperatures (Dataset B) to develop a standardised internal temperature (SIT) model for each dwelling. The modelling of the indoor and outdoor temperature needed to account for any non-linearity within the relationship, particularly at the colder/warmer extremes. Therefore, the regression used ordinary least squares (OLS) and tested several model forms, including: quadratic (i.e. squared and cubic) terms of outdoor temperature and also tested locally weighted polynomial regression (LOESS) to visualise model fit (not shown). The standardised internal temperature was estimated for each dwelling by regressing the mean hourly indoor temperature on outdoor temperature along with a squared term to allow for non-linear relationships using OLS.

This research was interested in examining periods when occupants would most likely be present within their dwelling during cold conditions and when the heating system was most likely being used. Using the research by Huebner et al., a *daytime heating* period was defined as 07:00 to 09:59 and 19:00 to 21:59, which are periods identified as having a higher probability of the heating system being used in English dwellings [11]. A *night-time* period was defined as 20:00 to 07:59. The method used here deviates from Oreszczyn et al. by using the periods identified by Huebner et al. as a proxy

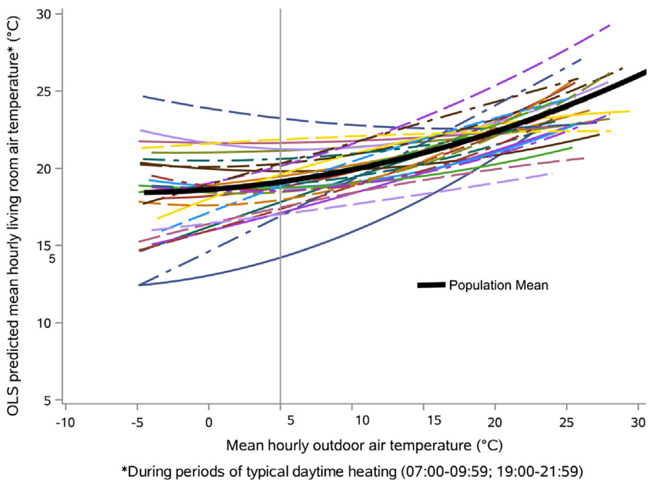

Fig. 3. OLS regression prediction of indoor mean hourly living room air temperatures and outdoor air temperature for a selection of dwellings.

for heating and occupancy and were used for the indoor to outdoor model and predicting the standardised temperature. The *daytime heating* period was used for the living room and hallway monitor and the *night-time* period was used for the bedroom monitor.

A regression function was derived for each dwelling and was used to predict the indoor temperature at an outdoor air temperature of 0 °C, 5 °C and 10 °C. Note that the analysis shown below focuses on the living room and bedroom temperatures because these are more likely indicators of the temperatures occupants would be exposed to during occupied periods.

3.3. E-value model

The thermal characteristic of the dwelling was estimated using a similar approach described by Oreszczyn et al. The E-value is the required energy used by the main heating system to maintain a 1 °C temperature difference between the outside and inside under steady state conditions. The method deviates slightly from that described by Oreszczyn et al. by including the ventilation characteristic of the dwelling, which would also influence the total heat demand of the dwelling (see Eq. (1)).

Eq. (1) – E-value equation

$$E = \left(\sum (U_i \times A_i) + (N \times V \times 0.33)\right)/\mu$$

Where Ui is the heat loss per square meter of surface area per degree Kelvin temperature difference between inside and outside ($W/m^2/K$) for the *i*th building element, Ai its surface area, N is the number of air changes (Nach), V is the volume of the dwelling (m^3), 0.33 is the specific heat capacity of air (J/K), and μ is the efficiency of the main heating device for the dwelling (0–1). The E-value is used to calculate heating energy by multiplying it by the temperature difference for a given period. The components of the E-value (i.e. fabric heat loss, ventilation heat loss and heating system efficiency) are commonly used in energy and indoor temperature analysis, but the advantage of the E-value is that it combines these into a single measure.

The inputs for calculating the E-value were determined using the property information collected as part of the EHS (i.e. the EFUS parent survey) to characterise the ventilation and fabric heat losses. The method used the survey information, such as dwelling type, construction year and region, to assign thermal properties of building materials (i.e. U-values) and 'rules-of-thumb' for ventilation

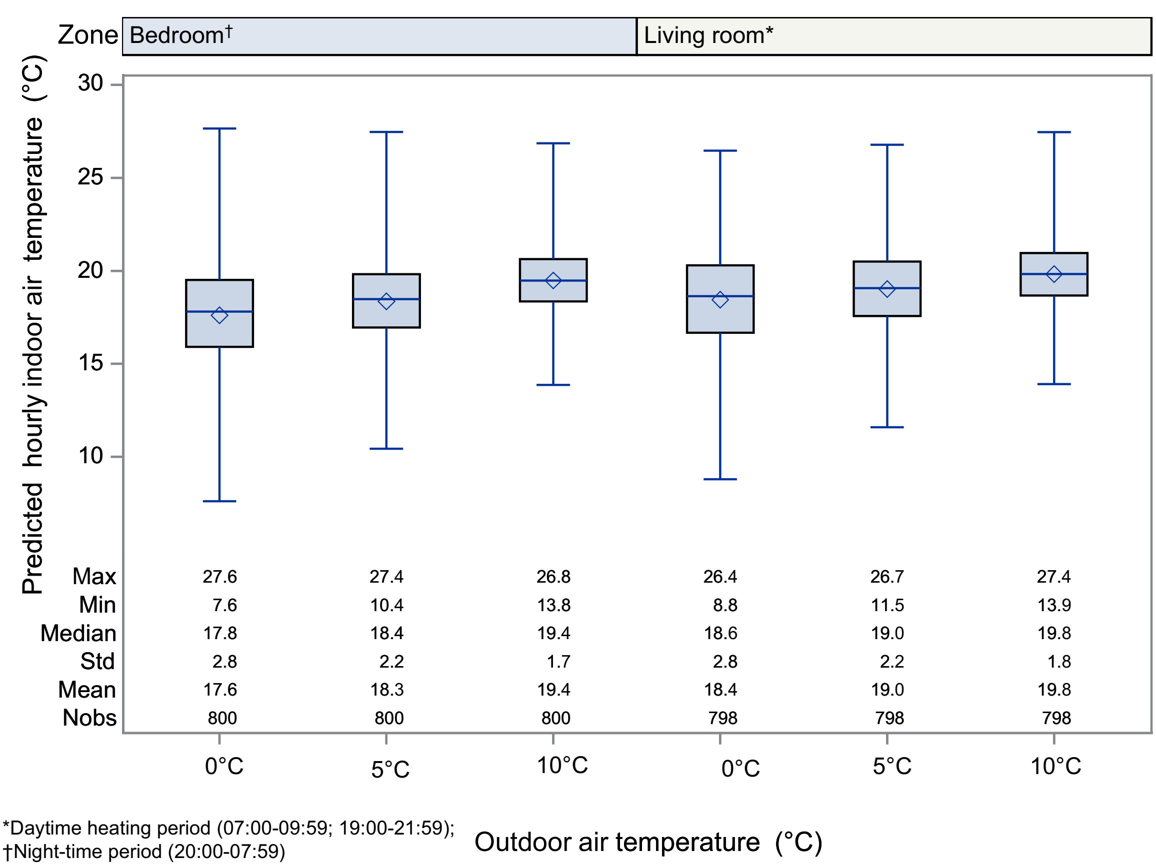

Fig. 4. OLS regression prediction of indoor mean hourly temperatures for 0 °C, 5 °C, and 10 °C outdoor air temperatures during periods defined as daytime heating.

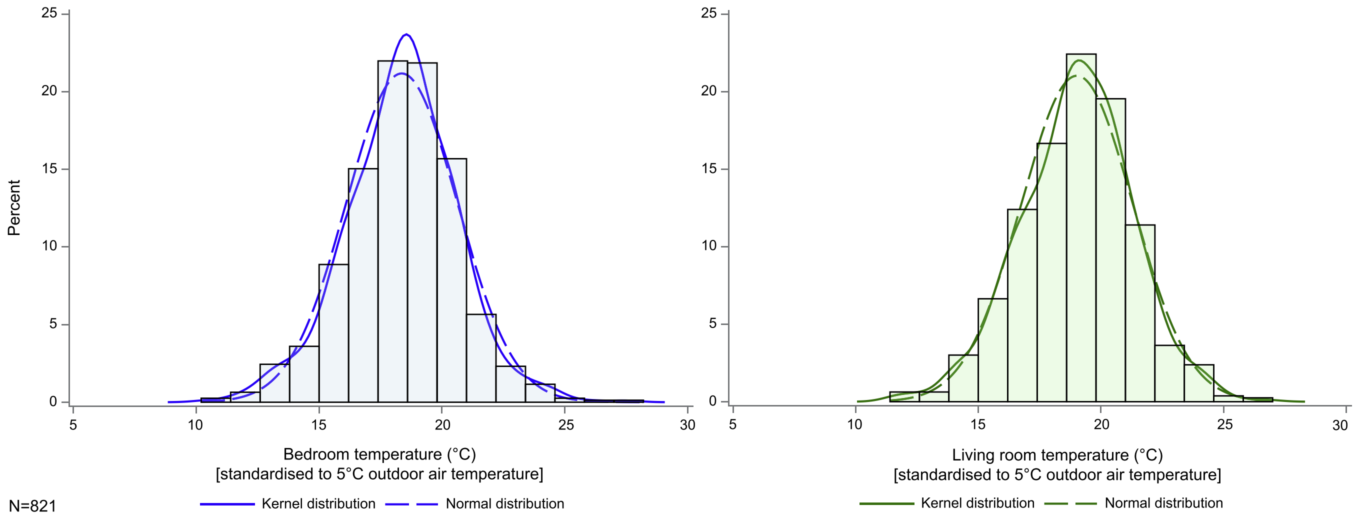

Fig. 5. Distribution of indoor living room and bedroom temperature standardised to 5 °C outdoor air temperatures.

rates related to the dwelling size, external area and active and passive ventilation components. The components used in estimating the E-value were drawn from the UK Government's Standard Assessment Procedure (SAP) method, which has been described and validated elsewhere in detail [23,24]. The SAP is used to benchmark the energy performance of the building in terms of how much energy a dwelling will consume at a set level of comfort and service using standard assumptions for occupancy and behaviour. The SAP measures the energy performance as: energy use per floor area, fuel-cost-based rating (i.e. SAP rating) and CO_2 emissions. For the heat loss calculations, the method here used the physical characteristics of the dwelling in the EHS to make inferences on the thermal and ventilation properties of the dwelling. The E-value for the EFUS 2011 sample was derived from the English Housing Survey housing stock data conversion process used by the UK Government in their energy demand stock modelling [24].

4. Results

First, in order to describe the context of the monitoring period (6 December 2010–13 February 2012) of the EFUS temperature data, the mean 24-h daily indoor and outdoor temperatures are shown in Table 2 and Fig. 1. The 24-h average indoor air temperatures within the group fluctuate between 17.3 °C and 22.2 °C throughout the year. The outdoor monitoring data shows several cool periods in December of 2010 and 2011 where the heating system would expect to be operating when occupied. Fig. 2 shows the delta between the mean of the mean daily temperatures for the living room, bedroom and hallway and the mean daily outdoor local weather station temperature. It is this mean temperature difference that in theory drives energy use. Mean daily indoor air temperatures are consistently greater than outdoor temperatures throughout the year, even during the summer period, which likely reflects solar and internal gains, and the envelope's thermal lag.

4.1. Indoor to outdoor air temperature relationship

Fig. 3 shows the results of the OLS regression of the hourly indoor temperature [Dataset B] against the outdoor air temperature (along with its square term) for living room temperatures for a random selection of dwellings in the sample. The results show that there are a number of different shapes present within the data, which illustrates the spread of hourly indoor temperatures exhibited within the dwellings during the *daytime heating* period at different outdoor temperatures. Broadly, however, most of the curves exhibit an upward slope as the outdoor temperatures decrease.

To make comparisons across the dwelling stock, indoor air temperatures at outdoor air temperatures of 0 °C, 5 °C and 10 °C were predicted using the OLS models. Fig. 4 shows the distribution of the living room, bedroom and hallway temperatures during the selected outdoor conditions. As the outdoor conditions become colder, the indoor conditions during expected daytime heating hours also become colder but with a greater variation in both bedrooms and living rooms; the standard deviations are almost 1 °C larger between 0 °C and 10 °C outdoor air temperatures. The distributions of indoor living room and bedroom temperature are moderately normally distributed (Fig. 5). In the following analysis of difference, a non-parametric approach is used to examine the significance of difference.

4.2. Determinants of indoor temperatures

The literature review identified that both the physical features of the dwelling along with household characteristics showed differences in indoor wintertime temperatures [7,17,18,25]. This section presents the results of significance testing for the determinants of indoor temperatures. These are shown as 'crude' differences from a baseline, i.e. they are not adjusted for other factors and are being shown to identify those factors that may help explain the standardised indoor temperature during wintertime conditions (i.e. 5 °C air temperature) for the subsequent model development. The significance tests use Kruskal-Wallis (KW), which are based on non-parametric distributions due to small sample sizes among the independent variables and that normality is not assumed.

Table 3 shows the standardised indoor living room and bedroom during daytime heating periods with outdoor air temperature conditions of 5 °C for a selection of dwelling physical characteristics. The results show that dwelling forms with greater exposed surface area (i.e. detached and semi-detached) have among the lowest temperatures in both living room and bedrooms, however these results are not significant. Older dwellings exhibit much cooler indoor temperatures, 17.9 °C and 17.3 °C in pre-1919 living rooms and bedrooms respectively, with more consistent temperatures among post-war dwellings. Local authority rented and registered social landlords (RSL) kept warmer dwellings than owner occupied or privately rented, particularly in the living rooms (which show a significant difference). As with dwelling form, larger dwellings, which would have greater volumes, were also colder than smaller

Table 3
Standardised indoor temperatures (at 5 °C outdoor air temperature) by property characteristics.

	Living Room (°C)					Bedroom temperature (°C)				
	N	% N	Mean	Diff from reference	Sig* of diff from reference	N	% N	Mean	Diff from reference	Sig* of diff from reference
Dwelling Type										
end-terrace	89	11.2	18.7			85	10.9	18.6		
mid-terrace	128	16	19.2	0.50	0.6271	128	16.5	18.3	−0.3	0.2901
semi-detached	261	32.7	18.6	−0.10	0.6575	256	32.9	18.3	0	0.4341
detached	196	24.6	18.5	−0.20	0.0686	193	24.8	18	−0.3	0.0672
Purpose built flat	109	13.7	19.7	1.00	0.0136	101	13	18.7	0.7	0.3463
Converted to flat	15	1.9	18	−0.70	0.2033	15	1.9	16.5	−2.2	0.1517
Dwelling Age										
Pre–1919	123	15.4	17.9			119	15.3	17.3		
1919–44	124	15.5	18.7	0.8	**0.0002**	122	15.7	18.1	0.8	0.0476
1945–64	201	25.2	19.2	1.3	**<.0001**	195	25.1	18.6	1.3	**<.0001**
1965–80	197	24.7	19.2	1.3	**<.0001**	192	24.7	18.6	1.3	**<.0001**
1981–90	79	9.9	19.2	1.3	**<.0001**	78	10	18.6	1.3	**0.0006**
Post–1990	74	9.3	18.8	0.9	0.035	72	9.3	18.5	1.2	**0.0009**
Tenure										
owner occupied	511	64	18.6			501	64.4	18.2		
private rented	65	8.1	18.6	0	0.567	63	8.1	17.9	−0.3	0.4428
local authority	103	12.9	20.2	1.6	**<.0001**	98	12.6	18.9	0.7	0.0284
RSL	119	14.9	19.5	0.9	**0.0027**	116	14.9	18.5	0.3	0.1403
Useable floor area										
<50sqm	48	6.7	19.5			46	6.6	18.5		
50–69sqm	154	21.5	18.8	−0.7	0.0487	152	21.7	18.3	−0.2	0.3233
70–89sqm	200	27.9	18.7	−0.8	**0.0081**	197	28.1	18.3	−0.2	0.2325
90–109sqm	115	16.1	19	−0.5	0.0691	113	16.1	18.4	−0.1	0.3898
>110sqm	199	27.8	18.5	−1	**<.0001**	194	27.6	18.1	−0.4	0.0435
Region										
North East	57	7.1	19			56	7.2	18.3		
North West	124	15.5	18.4	−0.6	0.3077	120	15.4	18	−0.3	0.652
Yorkshire and the Humber	102	12.8	18.6	−0.4	0.2781	100	12.9	17.8	−0.5	0.5061
East Midlands	77	9.6	19.2	0.2	0.5068	75	9.6	18.4	0.1	0.7306
West Midlands	70	8.8	18.7	−0.3	0.3909	69	8.9	18.3	0	0.9842
East	110	13.8	19.2	0.2	0.4121	108	13.9	18.6	0.3	0.2808
London	59	7.4	19	0	0.4378	58	7.5	18.5	0.2	0.4786
South East	121	15.2	19.1	0.1	0.9045	117	15	18.6	0.3	0.3161
South West	78	9.8	18.5	−0.5	0.3119	75	9.6	17.8	−0.5	0.2662

Note: *Significance tested using the non-parametric Kruskal-Wallis test.

dwellings. With a constant outdoor temperature of 5 °C there are no clear temperature patterns for dwelling location.

Table 4 shows indoor temperatures during 5 °C outdoor temperature conditions and household characteristics, which show limited significance tests from the comparison groups. However, the results show that as income lowers, indoor living room temperatures are warmer, but that bedroom temperatures are colder. In living rooms, younger households (<60 single or couple) without dependents tended to have lower temperatures, while older households (>60 single or couple) are highest; there is less difference among these groups in bedroom temperatures. Unemployed households have the lowest temperature in both the living room (17.3 °C) and bedroom (17.6 °C), while retired have the warmest living room (19.5 °C) and bedroom (18.5 °C) temperatures. Households who are considered vulnerable (either being in low income and/or in receipt of certain forms of benefits or income support) had colder dwellings than non-vulnerable households.

Internal temperature has been compared for households defined as being in fuel poverty using two definitions: the historic definition where 10% or more of the household income would in theory have to be spent to maintain comfortable conditions; and the recently introduced definition (i.e. low income high cost (LIHC)) attempts to capture the relative cost of both having a low income and of living in houses that are more costly to heat [26]. The results show that households estimated to be in fuel poverty using the 10% definition are also shown to have colder homes than non-fuel poor households. The historic 10% definition, is significantly different (using the applied KW test), while the LIHC definition shows less difference and of lower significance. Note that the LIHC definition uses both the expected heating energy demands accounting for the dwelling's energy performance along with the income level of the household to assess the notional fuel expenditure, while the 10% definition uses the income. The main effect is that a lower income household in a dwelling that is more energy efficient will be at lower risk of being classed as fuel poor under the LIHC.

Table 5 shows that dwellings that have greater energy efficiency measures have higher internal temperature, though again with limited significance from the comparison groups. Dwellings with no loft insulation have the lowest indoor living room temperatures and a small difference when looking at the presence of wall insulation. Dwellings with double glazing have significantly warmer indoor temperatures than dwellings with single glazing. When using an overall measure of energy performance, dwellings with larger E-values (i.e. the whole dwelling fabric and ventilation heat loss divided by heating system efficiency) are significantly colder than dwellings with smaller E-values. Note that this is not specifically a measure of energy performance, as large dwellings have more surface area and therefore greater heat losses. However, there is approximately 3 °C difference between the highest and lowest heat loss band of dwellings in living rooms and 1.8 °C in bedrooms. This trend is also shown when using the SAP measure of dwelling energy performance with lower energy performing dwellings having colder temperatures in both the living room and bedroom (a difference of 2.5 °C). The results show that for dwellings where

Table 4
Standardised indoor temperatures (at 5 °C outdoor air temperatures) by household characteristics.

	Living Room (°C)					Bedroom temperature (°C)				
	N	% N	Mean	Diff from mean	Sig* of diff from reference	N	% N	Mean	Diff from mean	Sig* of diff from reference
All household income										
lowest 20%	164	20.6	19			157	20.2	18		
quintile 2	170	21.3	18.8	−0.2	0.7441	167	21.5	17.7	−0.3	0.6354
quintile 3	164	20.6	19.2	0.2	0.3104	163	21	18.5	0.5	0.1492
quintile 4	161	20.2	18.8	−0.2	0.8133	159	20.4	18.6	0.6	0.0222
highest 20%	139	17.4	18.4	−0.6	0.1564	132	17	18.4	0.4	0.3481
Household composition										
couple, no dependents <60	129	16.2	18.6			124	15.9	18.6		
couple, no dependents >=60	183	22.9	19.4	0.8	0.0201	182	23.4	18.5	−0.1	0.4206
couple with dependent	174	21.8	19	0.4	0.9799	169	21.7	18.6	0	0.3831
single with dependent	44	5.5	18.8	0.2	0.4247	44	5.7	18.6	0	0.7482
other households	37	4.6	18.6	0	0.6766	36	4.6	17.7	−0.9	0.0607
one person <60	90	11.3	17.7	−0.9	**0.0025**	87	11.2	17	−1.6	**0.0035**
one person ≥60	141	17.7	19.2	0.6	0.3759	136	17.5	18.1	−0.5	0.1605
Employment status (primary) of HRP										
full time work	335	42	18.5			325	41.8	18.3		
part-time work	69	8.6	18.7	0.2	0.762	67	8.6	17.8	−0.5	0.2423
retired	282	35.3	19.5	1	**<.0001**	276	35.5	18.5	0.2	0.895
unemployed	23	2.9	17.3	−1.2	**0.0077**	21	2.7	17.6	−0.7	0.186
full time education	4	0.5	19.5	1	0.906	4	0.5	18.5	0.2	0.3714
other inactive	85	10.7	18.9	0.4	0.234	85	10.9	18.3	0	0.7754
Household on means tested benefit and low income										
Yes	207	25.9	19.3			201	25.8	18.2		
No	591	74.1	18.7	−0.6	0.0299	577	74.2	18.3	0.1	0.9441
Household vulnerable – on means tested or certain disability related benefits?										
Yes	260	32.6	19.3			253	32.5	18.3		
No	538	67.4	18.7	−0.6	**0.0041**	525	67.5	18.2	−0.1	0.8101
Fuel poverty – 10% definition (full income)										
Not in FP	689	86.3	18.9			673	86.5	18.4		
In FP	109	13.7	18.2	−0.7	**0.0057**	105	13.5	17.2	−1.2	**<.0001**
Fuel poverty – Low Income High Costs definition										
Not in FP	716	89.7	18.9			697	89.6	18.3		
In FP	82	10.3	18.4	−0.5	0.0863	81	10.4	17.6	−0.7	0.0216

Note: *Significance tested using the non-parametric Kruskal-Wallis test.

dampness is a problem in one or more rooms, both the living room and bedrooms are colder by 0.2 °C and 1.2 °C respectively. Hong et al. found that mould growth risk was higher among dwellings with colder temperatures (and therefore both the moisture content of the dwellings likely to be higher and colder surfaces) [27].

From the above analysis, those features that show significance in describing the indoor temperature during wintertime conditions using non-parametric tests are: dwelling age, size, household tenure, household composition, reference person employment status, benefit receipt, fuel poverty risk under 10% definition, fabric heat loss, energy performance rating, and window type. These are used in the modelling indoor temperature at different outdoor temperatures.

4.3. Model of indoor temperatures

Table 6 shows the results of a generalised linear regression model for the selected number of dwelling, household and energy performance characteristics, and Table 7 shows the model fit parameters. The mean standardised internal air temperature at 5 °C outdoor air temperature in the living room and bedroom are 16.7 °C and 16.1 °C respectively after adjusting for the selected dwelling features and household characteristics. The results of the model show the effect of exposed surface area as a proxy for heat loss, by way of dwelling type, with living room and bedroom temperatures becoming warmer. Living room temperatures in purpose built and converted flats are 1 °C and 1.4 °C warmer than detached dwellings, while bedroom temperatures are 0.8 °C and 1.4 °C. As dwelling age increases so does temperatures in both living room and bedrooms, with a notable exception for the most recent age band on post-1990 dwellings. Compared to the oldest dwellings, the newer dwellings are warmer (0.7 °C and 1 °C in living room and bedrooms) but slightly less than the 1920–1989 cohort. Compared to Table 3, the age related temperature differences are around 0.3 °C lower, but remain moderately significant even after controlling for other factors such as thermal heat loss

Table 5
Standardised indoor temperatures (at 5 °C outdoor air temperature) by dwelling energy performance characteristics.

	Living Room (°C)					Bedroom temperature (°C)				
	N	% N	Mean	Diff from mean	Sig of diff from mean	N	% N	Mean	Diff from mean	Sig* of diff from mean
Loft insulation thickness										
none	21	2.9	17.6			21	3	17.8		
<100 mm	138	19.3	18.9	1.3	0.3262	133	18.9	18.2	0.4	0.2677
100–150 mm	211	29.5	18.7	1.1	0.5937	209	29.8	18.3	0.5	0.372
>150 mm	346	48.3	18.8	1.2	0.4381	339	48.3	18.3	0.5	0.3727
Wall insulation type										
Cavity insulated	336	46.9	19.1			329	46.9	18.5		
Cavity uninsulated	205	28.6	18.7	−0.4	0.3333	202	28.8	18.1	−0.4	0.2557
Solid as built	134	18.7	18.4	−0.7	0.012	130	18.5	18.1	−0.4	0.0109
Other	41	5.7	17.7	−1.4	0.3311	41	5.8	17.8	−0.7	0.5642
Main heating system										
boiler with radiators	659	92	18.7			647	92.2	18.3		
storage radiators	34	4.7	19.2	0.5	0.1807	34	4.8	17.6	−0.7	0.0571
warm air system	6	0.8	19.3	0.6	0.9386	5	0.7	18.3	0	0.6592
room heater	11	1.5	16.8	−1.9	0.2517	11	1.6	16	−2.3	0.0547
other systems	1	0.1	18.9	0.2	0.9342	1	0.1	18.1	−0.2	0.8153
communal	5	0.7	24.2	5.5	**<.0001**	4	0.6		5	**<.0001**
E-value (W/K)								23.3		
1–100	17	2.4	20.8			15	2.1	19.4		
100–249	180	25.1	19.1	−1.7	0.0225	180	25.6	18.6	−0.8	0.726
250–499	369	51.5	18.9	−1.9	**0.0025**	361	51.4	18.3	−1.1	0.4107
500–greater	150	20.9	17.8	−3	**<.0001**	146	20.8	17.6	−1.8	0.0352
Energy efficiency (SAP09) rating										
<30	19	2.7	16.8			19	2.7	16.1		
30–50	175	24.4	18.3	1.5	0.021	169	24.1	17.9	1.8	0.0037
51–70	484	67.6	19	2.2	0.0022	478	68.1	18.5	2.4	**0.0003**
>70	38	5.3	19.3	2.5	**0.0006**	36	5.1	18.6	2.5	**0.0003**
Window type										
Single glazed	71	9.9	17.5			70	10	16.9		
Double glazed	635	88.7	18.9	1.4	**<.0001**	623	88.7	18.4	1.5	**<.0001**
Other	10	1.4	19	1.5	0.0224	9	1.3	18.1	1.2	0.0198
Dampness problems in one or more rooms										
not present	690	96.4	18.8			676	96.3	18.3		
problem present	26	3.6	18.6	−0.2	0.3145	26	3.7	17.1	−1.2	0.0579

Note: *Significance tested using the non-parametric Kruskal-Wallis test.

and dwelling size. This suggests there is an age specific factor that affects indoor temperature. Local authority tenured households experience significantly warmer bedroom and living room temperatures compared to owner occupied dwellings, which accounts for the higher temperatures within purpose built flats which comprise the bulk of this type of housing. Other related socio-economic variable of household income shows that in general as incomes increase so does adjusted indoor temperatures, in both bedroom and living rooms, like the crude values. Compared to single person households under 60 years of age, households that have more people and older occupants tend to be warmer in the living room. The bedroom temperatures (i.e. night periods) show that households with children are the warmest. Household composition becomes a significant predictor after adjusting for dwelling features and is clearly acting as a proxy for heating demand behaviours. Compared to working households, dwellings that were unemployed had colder living room temperatures, while retired households had the warmest living room. In bedrooms, there was a trend to decrease temperatures as full-time employment status reduced, except for retirees who had warmer bedrooms. Households in receipt of some benefits kept warmer daytime living room temperatures and cooler night-time bedroom temperatures compared to those not in receipt of benefits, but this difference was no longer significant once controlling for household characteristics and dwelling type. Finally, indoor temperatures are shown to decrease as dwelling thermal performance worsened (i.e. >E-value). Because the temperatures are adjusted for both dwelling size (i.e. floor area bands) and exposed surface area, the difference between thermal values is less, but remains significant at the highest heat loss band. The fuel poverty definitions were tested but were found to be not significant and therefore not included in the final model. Dwelling age, household composition and employment are among the strongest predictors of indoor temperature.

4.4. Indoor temperatures under colder/warmer conditions

Analysis was also performed to determine if the differences remained when the outdoor air temperature conditions were colder (0 °C) or warmer (10 °C) than 5 °C. The results (full tables shown in Appendix A) show that the trends in the differences were broadly similar, but that the magnitudes tended to be greater as outdoor conditions became colder. Fig. 4 showed that temperatures at the 10 °C were on average warmer than the indoor conditions at 0 °C and 5 °C outdoor by about 1 °C within the living rooms and 0.5 °C in the bedrooms. The trend across dwelling age was consistent at different outdoor conditions, with temperatures increasing (compared to the pre-1919 group) and then falling; the post-1990

Table 6
Model estimates of dwelling, household and energy performance characteristics and standardised internal temperature (at 5 °C outdoor air temperature) in living room and bedrooms.

	Living room SIT† at 5 °C outdoor				Bedroom SIT† at 5 °C outdoor			
Parameter	Estimate	SE	tValue	Pr > t*	Estimate	SE	tValue	Pr > t*
Intercept	16.7	0.7	23.1	**<.0001**	16.1	0.8	21.0	**<.0001**
Dwelling type								
detached	0.0	.	.	.	0.0	.	.	.
semi-detached	0.2	0.2	0.9	0.3561	0.5	0.2	2.0	0.0487
end-terrace	0.4	0.3	1.4	0.1639	0.7	0.3	2.3	0.0214
mid-terrace	0.8	0.3	2.8	0.0055	0.6	0.3	1.9	0.0542
converted	1.1	0.7	1.7	0.0857	0.8	0.7	1.2	0.2259
purpose built	1.5	0.4	3.8	**0.0001**	1.4	0.4	3.3	**0.001**
Dwelling age								
pre–1919	0.0	.	.	.	0.0	.	.	.
1919–44	1.0	0.3	3.6	**0.0004**	0.4	0.3	1.4	0.1573
1945–64	1.0	0.3	3.5	**0.0006**	0.9	0.3	2.9	0.0042
1965–80	0.9	0.3	3.0	**0.0026**	1.0	0.3	3.1	0.0022
1981–90	0.8	0.4	2.3	0.0225	0.9	0.4	2.4	0.0152
post–1990	0.5	0.4	1.5	0.1302	0.9	0.4	2.4	0.0189
Dwelling tenure								
owner-occupied	0.0	.	.	.	0.0	.	.	.
private-rented	0.2	0.3	0.5	0.5994	0.0	0.3	−0.1	0.9042
RSL	0.4	0.3	1.4	0.1707	0.0	0.3	0.2	0.8763
local authority	1.1	0.3	4.0	**<.0001**	0.7	0.3	2.4	0.018
Household income (AHC)								
lowest 20%	0.0	.	.	.	0.0	.	.	.
quintile 2	0.2	0.3	0.6	0.5657	−0.2	0.3	−0.6	0.5772
quintile 3	0.5	0.3	1.7	0.0901	0.3	0.3	0.9	0.3946
quintile 4	0.5	0.3	1.5	0.1322	0.6	0.4	1.5	0.129
highest 20%	0.4	0.4	1.1	0.2717	0.4	0.4	1.0	0.3162
Household composition								
single < 60	0.0	.	.	.	0.0	.	.	.
single ≥ 60	0.5	0.4	1.4	0.1709	0.2	0.4	0.6	0.5851
single w child(ren)	0.5	0.4	1.1	0.2703	1.0	0.4	2.3	0.0221
couple no child(ren) < 60	1.4	0.3	4.1	**<.0001**	1.2	0.3	3.4	**0.0007**
couple w child(ren)	1.4	0.3	4.3	**<.0001**	1.3	0.3	3.8	**0.0002**
couple no child(ren)≥60	1.4	0.3	4.0	**<.0001**	1.0	0.4	2.8	**0.0052**
multi-person households	0.7	0.4	1.6	0.1089	0.3	0.5	0.7	0.5044
HRP Employment								
full time work	0.0	.	.	.	0.0	.	.	.
full time education	1.3	1.1	1.3	0.2111	0.3	1.1	0.3	0.7948
part-time work	0.3	0.3	1.0	0.2978	−0.1	0.3	−0.2	0.8408
unemployed	−1.3	0.5	−2.5	0.0116	−0.4	0.6	−0.7	0.4916
retired	1.0	0.3	3.7	**0.0003**	0.6	0.3	2.1	0.0409
other inactive	0.1	0.3	0.3	0.7353	0.2	0.3	0.5	0.6196
Household in receipt of benefits								
no	0.0	.	.	.	0.0	.	.	.
yes	0.1	0.3	0.4	0.672	−0.3	0.3	−1.0	0.3098
Dwelling E-value¥ (W/K)								
1–100	0.0	.	.	.	0.0	.	.	.
100–249	−0.9	0.4	−2.1	0.0379	−0.2	0.4	−0.5	0.6119
250–499	−0.9	0.5	−1.8	0.0725	−0.3	0.5	−0.6	0.5351
≥500	−1.7	0.6	−3.0	0.0028	−1.0	0.6	−1.7	0.0971

†Adjusted for dwellings size bands and government office region; *Significant to the 95% confidence level; ¥The E-value is used as a proxy for fabric and heating system energy performance.

had the same temperature difference to the oldest dwellings group as the 1919-44 group.

The relationship between the energy performance of the dwelling and living room and bedroom air temperature is shown in Tables 8 and 9 respectively. The tables show the difference in temperature for both the E-value and SAP under colder and warmer outdoor conditions, adjusted for the variables listed in Table 6. Compared to the least efficient dwellings, i.e. those with a greater E-value and lower SAP, more efficient dwellings have warmer indoor temperatures at all the selected outdoor conditions. There is a 3 °C difference between the most efficient group of dwellings (i.e. E-value < 100 W/K) and the least efficient (i.e. >500 W/K). This trend is also seen when using the SAP measure with around 2.5 °C difference between the highest and lowest rating bands.

Fig. 6 shows the adjusted living room and bedroom SIT as the difference from the group mean by dwelling age band (A) and income (B). For dwelling age, when compared to the mean, pre-1919 dwellings are colder in both the living room and bedrooms, while the newest dwellings are warmer in the bedroom but colder in the living room. For income, lower incomes are also colder than higher incomes, after adjustment. As outdoor conditions become colder there is little difference within the age and income groups. There is only a slight difference for the pre-1919 dwellings bedroom temperatures (i.e. 0.3 °C between 0 °C and 10 °C outdoor air temperatures).

Table 7
Fit parameters for living room and bedroom SIT models shown in Table 8.

Living room temperature at 5 °C external model parameters					
Source	DF	Sum of Squares	Mean Square	FValue	Pr > F
Model	44	949.1	21.6	5.11	<0.0001
Error	753	3179.4	4.2		
CorrectedTotal	797	4128.5			
R-Square	CoeffVar	RootMSE	Living room SIT Mean		
0.23	10.85	2.06	19.02		
Bedroom temperature at 5 °C external model parameters					
Source	DF	Sum of Squares	Mean Square	FValue	Pr > F
Model	44	587.1	13.3	2.89	<0.0001
Error	733	3384.7	4.6		
CorrectedTotal	777	3971.8			
R-Square	CoeffVar	RootMSE	Bedroom SIT Mean		
0.15	11.70	2.15	18.36		

Table 8
Adjusted standardised indoor living room temperatures at 0 °C, 5 °C and 10 °C outdoor air temperature by metrics of dwelling thermal and energy performance.

	Mean Standardised Living Room Temperature (°C)											
	0 °C outdoor air temperature				5 °C outdoor air temperature				10 °C outdoor air temperature			
Parameter	Estimate	SE	tValue	Pr > |t|	Estimate	SE	Error	t Value	Estimate	SE	tValue	Pr > |t|
Model 1: Dwelling E-value (W/K)												
1–100	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.
100–249	−0.9	0.4	−2.1	0.0379	−0.2	0.4	−0.5	0.6119	−1.0	0.5	−1.9	0.0556
250–499	−0.9	0.5	−1.8	0.0725	−0.3	0.5	−0.6	0.5351	−1.0	0.6	−1.7	0.0958
≥500	−1.7	0.6	−3.0	0.0028	−1.0	0.6	−1.7	0.0971	−2.0	0.7	−2.9	0.0043
Model 2: Energy efficiency (SAP09) rating												
less than 30	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.
30 to 50	1.3	0.7	2.0	0.045	2.1	0.7	2.9	0.0036	1.1	0.5	2.0	0.0443
51 to 70	1.5	0.7	2.2	0.0273	2.3	0.7	3.2	0.0014	1.1	0.5	2.0	0.0446
more than 70	1.9	0.8	2.4	0.0172	2.3	0.8	2.7	0.0071	1.5	0.6	2.4	0.0177

†Adjusted for dwellings type, age, tenure and size bands; and, household income, composition, employment, benefit receipt, and government office region.

Table 9
Adjusted standardised indoor living room temperatures at 0 °C, 5 °C and 10 °C outdoor air temperature by metrics of dwelling thermal and energy performance.

	Mean Standardised Bedroom Temperature† (°C)											
	0 °C outdoor air temperature				5 °C outdoor air temperature				10 °C outdoor air temperature			
Parameter	Estimate	SE	tValue	Pr > |t|	Estimate	SE	Error	t Value	Estimate	SE	tValue	Pr > |t|
Model 1: Dwelling E-value (W/K)												
1–100	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.
100–249	0.0	0.6	0.0	0.9816	−0.8	0.3	−2.4	0.0173	−0.4	0.3	−1.2	0.2462
250–499	−0.2	0.7	−0.3	0.769	−0.8	0.4	−2.1	0.041	−0.4	0.4	−1.1	0.279
≥500	−1.1	0.8	−1.4	0.1554	−1.4	0.4	−3.2	0.0013	−0.9	0.5	−2.0	0.0446
Model 2: Energy efficiency (SAP09) rating												
less than 30	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.
30–50	1.4	0.6	2.5	0.0113	0.8	0.4	2.0	0.0465	0.8	0.4	1.9	0.0573
51–70	1.4	0.6	2.6	0.01	0.7	0.4	1.8	0.0798	0.7	0.4	1.7	0.0974
more than 70	1.5	0.7	2.2	0.0265	1.2	0.5	2.3	0.0194	0.8	0.5	1.5	0.1301

†Adjusted for dwellings type, age, tenure and size bands; and, household income, composition, employment, benefit receipt, and government office region.

5. Discussion

Using the English Follow Up Survey (EFUS), the largest cross-sectional survey of dwelling characteristics and indoor temperatures measurements in England, this study examined the relationship between living room and bedroom indoor temperature and a selection of dwelling features (dwelling type, age, tenure, size and location), household characteristics (household income, composition, income, employment, benefits receipt, vulnerability and fuel poverty) and energy and environmental performance (loft and wall insulation, E-value and SAP, glazing and condensation). This study differs from previous studies looking at indoor temperatures in English homes [7,15,17,18] in terms of its representativeness of English dwellings, the duration of the monitoring period, and the use of different outdoor conditions when standardising for comparison.

When looking at the determinants in isolation (i.e. Tables 3–5), a number of dwelling features and household characteristics were shown to have significant differences between classes, these included: dwelling age, size, household tenure, household composition, reference person employment status, benefit receipt, fuel poverty risk under 10% definition, fabric heat loss, energy performance rating, and window type. However, when used in combination in a model to predict indoor temperatures, few remained strong predictors and these tended to relate to dwelling heat loss features (i.e. exposed wall area through dwelling type and

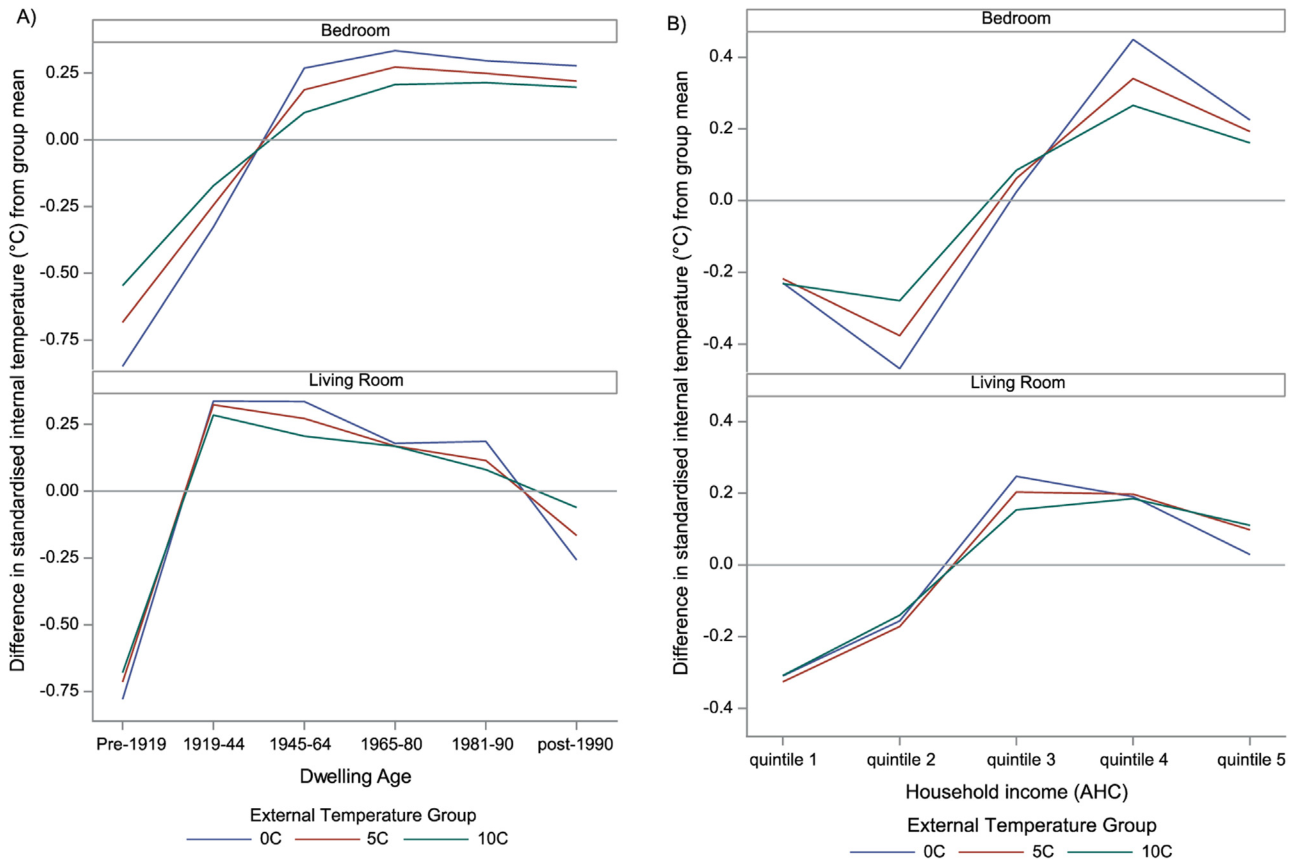

Fig. 6. Difference in standardised internal temperature by dwelling age band (A) and household income (B) for different outdoor air temperatures.

fabric thermal performance through E-value). The discussion below focuses on the adjusted model results of Table 6.

With regards to the age of the property (Q1), the analysis showed that as dwelling age increased, so did indoor temperatures in both the living room and bedrooms, after adjusting for a selection of dwelling and household characteristics. Post-war dwellings, i.e. those built between 1945 and 1989, were the warmest, while the newest dwellings (post-1990) tended to be on average colder than the post-war cohort by almost 0.3 °C in the living room and what would be during periods most likely to be occupied. However, there were only minor differences during night-time periods. Between the unadjusted and adjusted analyses, dwelling age remained a significant determinant even after accounting for other measures of thermal performance. While many dwellings built in the post-war period are smaller than older dwellings and a large number being purpose built flats, these factors were adjusted for and the fact that newer dwellings have temperatures similar to those built in 1919–1944 is unusual, since newer dwellings are built to building regulation energy performance standards that should far exceed the older cohort. It could be that many of those post-war dwellings have been retrofit to a higher energy performance standard, but it is unlikely that these would be equivalent to the standards regulating newer dwellings and this is difficult to determine from the data. Another consideration is that people who live in newer dwellings modify their behaviour to keep lower indoor temperatures for reasons aside income, household size and ownership. For example, in newer buildings the fabric and heating system will be co-designed and more efficient and therefore monitored temperatures and comfort temperatures may be closer due to reduced heat losses. Regardless, we find evidence to support the hypothesis that on average older dwellings are colder than newer dwellings, after being adjusted, but that the newest dwellings are not the warmest, and this may reflect energy performance not captured within the E-value measure and occupant behaviours and pReferences

The analysis also shows that as some indicators of socio-economic status increase (i.e. income, employment) adjusted indoor temperatures also increased (Q2). Compared to the lowest income quintile, households with higher incomes kept warmer temperatures, but this was not a linear increase and the highest incomes were not on average the warmest. Further, household composition also reflected differences that might act as a socio-economic proxy. Households with couples (with or without children) were among the warmest and may reflect the increased chance of two incomes contributing to household fuel expenditure. When looking at employment, unemployed households had both the lowest daytime living room temperatures and bedroom night-time temperatures suggesting that these households could be maintaining quite a low indoor temperature of below 16 °C on average depending on their dwelling and household characteristics. Older and retired households, however, maintained among the highest indoor temperatures, which is aligned with the findings of Wilkinson et al. However, when looking at both age and income, the adjusted temperatures show that retired households with low incomes are colder than their higher incomes peers, which was also shown by Oreszczyn et al. in their study of older vulnerable households. Also, there was a significant difference for households living in local authority rented properties, another measure of socio-economic status, who were on average 1 °C warmer during daytime heating periods and 0.7 °C warmer overnight. There are several potential reasons why local authority dwellings have the highest temperatures, which could include: better building management, concern by councils of providing heating, and/or building features not picked up by dwelling type, size or performance. While there appears to be evidence to support the hypothesis that indoor temperatures are warmer among higher socio-economics classes, it would also appear that those households living in rented local authority dwellings are maintaining higher temperatures.

There appears to be little change in these trends when looking at lower or higher outdoor temperature conditions (i.e. 0 °C and 10 °C). The research question sought to determine whether older dwellings became much colder compared to newer dwellings when outdoor conditions became colder, with the premise being that older (and less efficient) dwellings would become more difficult and expensive to heat and therefore the indoor temperature conditions would become colder (Q3). The analysis results do not support this. It may be that in these older dwellings the occupants adjust the heating controls to meet their thermal comfort demands and are therefore willing to pay for this comfort. On the other hand, the analysis used monitors that were placed in the main living spaces (bedroom and living room) and it may be that other spaces are used less and/or no longer heated to focus the heat where it is most needed.

Finally, the analysis also shows that as energy performance becomes worse (i.e. higher E-values), adjusted indoor temperatures become colder. As compared to the most efficient homes, those in the least efficient band are on average 1.7 °C and 1 °C colder in the living room and bedroom respectively. The results, which is moderately significant even after adjustment of other variables, suggests that energy performance is an important determinant of indoor temperature that may lead to a low indoor temperature exposure.

In support of the existing evidence base, this study shows there is good evidence that households in the lowest socio-economic conditions are the coldest and that this will be compounded by living in dwellings with poor energy performance.

Are the findings of the monitoring analysis the actual experienced temperatures? There are no doubt mechanisms by which people will adapt their activities or conditions to mitigate or avoid these cold conditions. For example, by leaving the home or wearing more clothing. It is important to note that this analysis is not estimating the determinants of the comfort (or operative) temperature that are typically used as a measure of thermal comfort. However, despite this caveat there is evidence for England to show that households with characteristics of low indoor temperatures from this study are in fact being exposed to the cold [28,29]. Also, it was shown that among English homes where the indoor living room and bedrooms temperatures were below 19 °C dry-bulb had a consistently low comfort vote [30].

What does this mean for policies that have sought to address energy performance of dwellings and indoor temperature conditions? Policies in England that focus on households in lower socio-economic conditions will likely find an unmet need for improved indoor temperature conditions and the effect of a retrofit, for example, will likely show a combination of energy savings and increase in indoor temperature. However, what this also means is that policies that have an objective of improving indoor temperatures that target on socio-economic conditions will need to also account for underlying energy performance. For example, a low-income household living in a purpose built flat is likely to be as warm or warmer than a high-income household living in a pre-1919 dwelling. To date, however, many policies do not have a consistent method of including energy performance as part of the targeting process [31]. In England, the Energy Company Obligation scheme, which focuses on 'hard-to-treat' dwellings (i.e. solid walled dwellings, off the gas grid, no loft spaces, and high-rise flats) uses SAP as part of the assessment, but not specifically as a targeting mechanism in part due to the lack of available data [32]. This analysis of temperatures could also be used help define the features of a household and dwelling where the risk of low temperature exposure is increased and thereby tailoring the payment to reflect the risk (i.e. larger older homes alongside lower incomes and older age). For example, the UK Government's Warm Homes Discount Scheme that provides fuel payments (~ £140 per year) to low income pensioners could be adjusted based on the expected energy performance of the dwelling.

This approach to analysis could be expanded to other countries where similar data sources are available to try and quantify the contribution that household and dwelling features have in indoor temperatures among the broader population. In the UK and Europe, where energy performance certificates are required when dwellings are sold and let, there may be an opportunity to focus programmes that seek to improve indoor temperature conditions towards dwellings that are both energy inefficient and occupied by households in lower socio-economic status. The approach was used in the final scheme year of the Warm Front programme [33].

5.1. Strengths and weaknesses

This analysis has included several novel methods for analysing indoor temperatures and has updated the evidence base of past studies that were limited by sampling. In terms of the implication for health, exposure to colder indoor temperatures during winter time conditions, has been shown to increase the risk of cardiovascular disease [7]. This analysis used the work by Huebner et al. to select daytime periods when heating patterns suggested households were typically demanding heat, i.e. 07:00–09:59 and 19:00–21:59). The night-time period of 20:00–07:00) temperatures was selected as it was likely that occupants would typically be at home and sleeping. Although the temperature data does not provide a definitive means to identify when households were present within the dwelling, the use of heating period to define typically occupancy could provide an appropriate proxy for determining likely periods of exposure.

There are several strengths and weaknesses that should be considered when interpreting the results of the analysis. First, although the EFUS is the largest cross-sectional survey representative of English households containing continuous temperature measurements in England, the sample size (i.e. N = 821) remains small and caution should be applied when extending the results to the whole population for the reason that temperature was not one of the sampling variables. While potentially erroneous data points were excluded from the data, there is a risk that the locations of the monitors were not representative of the temperature ranges experienced by the occupants. This could be because the monitors were not placed in locations that were commonly occupied or that measurements were being influence by other unknown factors. Finally, the categorical data used in the analysis is a snap shot pertaining to the moment of the survey and this means that there is a risk that some of the categories of variables may have changed between the time of the survey and the measurement campaign.

Going forward, further work is needed to better understand what happens to indoor temperature conditions within dwellings following energy performance retrofits and how socio-economic conditions affect thermal conditions. There is also a need to better understand the relationship between health and exposure to indoor thermal conditions. Although a number of studies have illustrated the important role that temperature plays in household health [7,8,13], it is unclear how building energy performance and energy use modify health outcomes.

6. Conclusions

Living room and bedroom temperatures can give a useful indication of the wintertime temperature exposure of a household. Energy performance and household socio-economic conditions, such as household composition, are important determinants of indoor temperature during wintertime conditions. A large proportion of the sample dwellings had indoor air temperatures below 18 °C during winter time conditions, which is known to be associated with negative comfort votes.

In designing policies to improve indoor thermal conditions, policymakers will need to consider underlying energy performance of the dwelling. The use of detailed building data alongside temporal monitoring gives a resource by which to examine temperature exposure across the population. Policies that are aiming to assist households with wintertime heating can use these results to determine those households with the highest risk of having low temperature during wintertime conditions. Future data resources that provide a measure of energy performance, such as energy performance certificates, may also be useful for further targeting these inefficient dwellings in areas of low socio-economic conditions. Energy efficiency policies that focus on both energy performance and temperature exposure could achieve broader health and wellbeing co-benefits.

Funding

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) funded 'Research Councils UK (RCUK) Centre for Energy Epidemiology' under EP/K011839/1, the EPSRC funded 'CBES Platform Grant' under EP/I02929X/1, and the National Institute for Health Research (NIHR) funded 'The impact of home energy efficiency interventions and winter fuel payments on winter- and cold-related mortality and morbidity in England: evaluation of a natural experiment' under PHR − 11/3005/31.

Acknowledgements

The authors are grateful for the support that Department of Business, Energy and Industrial Strategy (BEIS) for permission to use the EFUS data.

Appendix A. – Determinants of standardised indoor temperature at 0 °C and 10 °C outdoor temperatures.

see Table A1

Table A1
Model estimates of dwelling, household and energy performance characteristics and standardised internal temperature† (at 0 °C and 10 °C) in living room and bedrooms.

	Living room temperature at 0 °C external				Bedroom temperature at 0 °C external				Living room temperature at 10 °C external				Bedroom temperature at 10 °C external			
Parameter	Estimate	SE	tValue	Pr > |t|	Estimate	SE	tValue	Pr > |t|	Estimate	SE	tValue	Pr > |t|	Estimate	SE	tValue	Pr > |t|
Intercept	15.5	0.9	17.2	**<.0001**	14.7	1.0	14.9	**<.0001**	18.0	0.6	31.1	**<.0001**	17.8	0.6	30.2	**<.0001**
Dwelling type																
detached	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.
semi-detached	0.3	0.3	1.1	0.2941	0.6	0.3	1.9	0.0556	0.2	0.2	0.8	0.4074	0.4	0.2	2.3	0.0245
end-terrace	0.5	0.4	1.3	0.1801	0.9	0.4	2.2	0.0318	0.3	0.2	1.4	0.1622	0.6	0.2	2.5	0.013
mid-terrace	1.1	0.4	2.8	0.0052	0.7	0.4	1.8	0.0776	0.7	0.2	2.7	0.0074	0.6	0.2	2.3	0.0219
converted	1.4	0.8	1.7	0.0945	1.0	0.9	1.2	0.2394	0.8	0.5	1.6	0.1075	0.4	0.5	0.8	0.4089
purpose built	1.8	0.5	3.7	**0.0003**	1.5	0.5	2.9	0.0034	1.2	0.3	3.9	**0.0001**	1.1	0.3	3.4	**0.0006**
Dwelling age																
pre–1919	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.
1919–44	1.1	0.4	3.1	0.0023	0.5	0.4	1.3	0.1888	1.0	0.2	4.1	**<.0001**	0.4	0.2	1.6	0.117
1945–64	1.1	0.4	3.1	**0.0019**	1.1	0.4	2.9	0.0041	0.9	0.2	3.9	**0.0001**	0.6	0.2	2.8	0.0057
1965–80	1.0	0.4	2.6	**0.0087**	1.2	0.4	3.0	0.003	0.8	0.2	3.6	**0.0003**	0.8	0.2	3.2	0.0017
1981–90	1.0	0.5	2.1	0.0331	1.1	0.5	2.3	0.0198	0.8	0.3	2.6	**0.0091**	0.8	0.3	2.6	0.0102
post–1990	0.5	0.5	1.2	0.2483	1.1	0.5	2.3	0.0222	0.6	0.3	2.1	0.0333	0.7	0.3	2.5	0.0121
Dwelling tenure																
owner-occupied	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.
private-rented	−0.1	0.4	−0.4	0.7132	−0.2	0.4	−0.5	0.5986	0.3	0.2	1.4	0.1567	0.1	0.2	0.4	0.7071
RSL	0.4	0.3	1.3	0.1935	0.1	0.4	0.2	0.867	0.3	0.2	1.4	0.1726	0.0	0.2	0.0	0.9855
local authority	1.4	0.4	3.8	**0.0001**	0.8	0.4	2.1	0.0329	0.9	0.2	3.8	**0.0001**	0.6	0.2	2.4	0.0158
Household income (AHC)																
lowest 20%	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.
quintile 2	0.2	0.3	0.5	0.6472	−0.2	0.4	−0.7	0.5101	0.2	0.2	0.8	0.4327	0.0	0.2	−0.2	0.8279
quintile 3	0.6	0.4	1.4	0.1525	0.3	0.4	0.6	0.5472	0.5	0.2	1.9	0.0647	0.3	0.3	1.3	0.2122
quintile 4	0.5	0.4	1.2	0.2492	0.7	0.5	1.4	0.1493	0.5	0.3	1.8	0.0766	0.5	0.3	1.8	0.0794
highest 20%	0.3	0.5	0.7	0.4814	0.5	0.5	0.9	0.3865	0.4	0.3	1.4	0.1746	0.4	0.3	1.2	0.2136
Household composition																
single <60	0.0	.	.	.	0.0				0.0	.	.	.	0.0	.	.	.
single ≥60	0.6	0.4	1.4	0.1757	0.2	0.5	0.4	0.6725	0.3	0.3	1.2	0.2363	0.1	0.3	0.5	0.6161
single w child(ren)	0.5	0.5	1.0	0.3173	1.2	0.6	2.1	0.0325	0.4	0.3	1.1	0.2809	0.7	0.3	2.2	0.0263
couple no child(ren) <60	1.8	0.4	4.5	**<.0001**	1.6	0.4	3.6	**0.0004**	0.9	0.3	3.5	**0.0005**	0.8	0.3	2.8	**0.0047**
couple w child(ren)	1.9	0.4	4.5	**<.0001**	1.7	0.4	3.8	**0.0002**	1.0	0.3	3.7	**0.0002**	0.9	0.3	3.4	**0.0007**
couple no child(ren) ≥60	1.8	0.4	4.2	**<.0001**	1.2	0.5	2.6	**0.0083**	1.0	0.3	3.5	**0.0004**	0.7	0.3	2.7	**0.0083**
multi−person households	1.1	0.5	2.0	0.0509	0.5	0.6	0.9	0.3848	0.4	0.3	1.1	0.2762	0.1	0.4	0.4	0.702
HRP Employment																
full time work	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.
full time education	2.2	1.3	1.6	0.102	0.9	1.4	0.6	0.5199	0.7	0.9	0.8	0.4363	−0.1	0.9	−0.1	0.9161
part-time work	0.4	0.4	1.2	0.2274	0.0	0.4	0.1	0.9087	0.2	0.2	0.7	0.5182	−0.1	0.2	−0.5	0.6005
unemployed	−1.7	0.6	−2.6	**0.0087**	−0.8	0.7	−1.1	0.2834	−0.9	0.4	−2.3	0.0229	−0.1	0.4	−0.2	0.8221
retired	1.2	0.3	3.4	**0.0007**	0.7	0.4	1.9	0.0558	0.8	0.2	3.5	**0.0006**	0.4	0.2	2.0	0.0494
other inactive	0.0	0.4	0.0	0.9754	0.2	0.4	0.4	0.6575	0.2	0.2	0.8	0.4432	0.1	0.2	0.6	0.555
Household in receipt of benefits																
no	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.
yes	0.0	0.3	0.1	0.9038	−0.4	0.4	−1.1	0.2593	0.2	0.2	0.8	0.4076	−0.1	0.2	−0.6	0.5596
Dwelling e−value (W/K)																
1–100	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.	0.0	.	.	.
100–249	−1.0	0.5	−1.9	0.0556	0.0	0.6	0.0	0.9816	−0.8	0.3	−2.4	0.0173	−0.4	0.3	−1.2	0.2462
250–499	−1.0	0.6	−1.7	0.0958	−0.2	0.7	−0.3	0.769	−0.8	0.4	−2.1	0.041	−0.4	0.4	−1.1	0.279
≥500	−2.0	0.7	−2.9	**0.0043**	−1.1	0.8	−1.4	0.1554	−1.4	0.4	−3.2	**0.0013**	−0.9	0.5	−2.0	0.0446

References

[1] J. Gilbertson, M. Grimsley, G. Green, Psychosocial routes from housing investment to health: evidence from England's home energy efficiency scheme, Energy Policy 49 (2012) 122–133, http://dx.doi.org/10.1016/j.enpol.2012.01.053.

[2] J.D. Healy, J.P. Clinch, Fuel poverty, thermal comfort and occupancy: results of a national household-survey in Ireland, Appl. Energy 73 (2002) 329–343, http://www.sciencedirect.com/science/article/pii/S0306261902001150, (accessed September 26, 2013).

[3] H. Thomson, S. Thomas, E. Sellstrom, M. Petticrew, Housing Improvements for Health and Associated Socio-economic Outcomes, John Wiley & Sons, Ltd, 2013, http://dx.doi.org/10.1002/14651858.cd008657.pub2.

[4] ONS, Excess Winter Mortality in England and Wales, 2013/14 (Provisional) and 2012/13 (Final), London, UK, 2014. http://www.ons.gov.uk/ons/dcp171778_387113.pdf.

[5] J.P. Clinch, J.D. Healy, Cost-benefit analysis of domestic energy efficiency, Energy Policy 29 (2001) 113–124, http://dx.doi.org/10.1016/S0301-4215(00)00110-5.

[6] R. Wookey, A. Bone, C. Carmichael, A. Crossley, Minimum Home Temperature Thresholds for Health in Winter –A Systematic Literature Review About Public Health, 2014.

[7] P. wilkinson, M. landon, B. armstrong, S. stevenson, M. McKee, T. fletcher, in: Cold Comfort: the Social and Environmental Determinants of Excess Winter Death in England, 1986–1996, Joseph Rowntree Foundation, York, UK, 2001.

[8] I. Shiue, M. Shiue, Indoor temperature below 18 (C accounts for 9% population attributable risk for high blood pressure in Scotland, Int. J. Cardiol. 171 (2014) e1–2, http://dx.doi.org/10.1016/j.ijcard.2013.11.040.

[9] DECC, Great Britain's housing energy factfile Report 2011, Department of Energy and Climate Change, London, UK, 2012.

[10] B. Lin, Z. Wang, Y. Liu, Y. Zhu, Q. Ouyang, Investigation of winter indoor thermal environment and heating demand of urban residential buildings in China's hot summer – Cold winter climate region, Build. Environ. 101 (2016) 9–18, http://dx.doi.org/10.1016/j.buildenv.2016.02.022.

[11] G.M. Huebner, M. McMichael, D. Shipworth, M. Shipworth, M. Durand-Daubin, A. Summerfield, Heating patterns in English homes: comparing results from a national survey against common model assumptions, Build. Environ. 70 (2013) 298–305, http://dx.doi.org/10.1016/j.buildenv.2013.08.028.

[12] A. Mavrogianni, F. Johnson, M. Ucci, A. Marmot, J. Wardle, T. Oreszczyn, A. Summerfield, Historic variations in winter indoor domestic temperatures and potential implications for body weight gain, Indoor Built Environ. 22 (2013) 360–375, http://dx.doi.org/10.1177/1420326X11425966.

[13] R. Jevons, C. Carmichael, A. Crossley, A. Bone, Minimum indoor temperature threshold recommendations for English homes in winter –A systematic review, Public Health 136 (2016) 4–12, http://dx.doi.org/10.1016/j.puhe.2016.02.007.

[14] DECC, Annual Fuel Poverty Statistics Report, DECC, London, UK, 20142014 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/319280/Fuel_Poverty_Report_Final.pdf.

[15] K. Vadodaria, D.L. Loveday, V. Haines, Measured winter and spring-time indoor temperatures in UK homes over the period 1969–2010: A review and synthesis, Energy Policy. 64 (2014) 252–262, http://dx.doi.org/10.1016/j.enpol.2013.07.062.

[16] DETR, English House Condition Survey 1991: Energy Report, The Stationery Office, 1996.

[17] S. Kelly, M. Shipworth, D. Shipworth, M. Gentry, A. Wright, M. Pollitt, D. Crawford-Brown, K. Lomas, Predicting the diversity of internal temperatures from the English residential sector using panel methods, Appl. Energy 102 (2013) 601–621, http://dx.doi.org/10.1016/j.apenergy.2012.08.015.

[18] T. Oreszczyn, S.H. Hong, I. Ridley, P. Wilkinson, Determinants of winter indoor temperatures in low income households in England, Energy Build. 38 (2006) 245–252, http://dx.doi.org/10.1016/j.enbuild.2005.06.006.

[19] I.G. Hamilton, D. Shipworth, A.J. Summerfield, P. Steadman, T. Oreszczyn, R. Lowe, Uptake of energy efficiency interventions in English dwellings, Build. Res. Inf. 42 (2014) 255–275, http://dx.doi.org/10.1080/09613218.2014.867643.

[20] DECC, BRE, Energy Follow-Up Survey 2011 – Report 1: Summary of findings, London, UK, 2014.

[21] DECC, BRE, Energy Follow-Up Survey 2011 – Report 11: Methodology, London, UK, 2014.

[22] Met Office, Met Office Integrated Data Archieve System (MIDAS), (2013). http://catalogue.ceda.ac.uk/uuid/245df050d57a500c183b88df509f5f5a.

[23] M. Hughes, J. Palmer, P. Pope, A Guide to The Cambridge Housing Model, Department of Energy and Climate Change, 2013 (London, UK,).

[24] M. Hughes, J. Palmer, V. Cheng, D. Shipworth, Sensitivity and uncertainty analysis of England's housing energy model, Build. Res. Inf. 41 (2013) 156–167, http://dx.doi.org/10.1080/09613218.2013.769146.

[25] G.M. Huebner, M. McMichael, D. Shipworth, M. Shipworth, M. Durand-Daubin, A.J. Summerfield, The shape of warmth: temperature profiles in living rooms, Build. Res. Inf. 1 12 (2014), http://dx.doi.org/10.1080/09613218.2014.922339.

[26] DECC, Fuel Poverty: a Framework for Future Action, The Stationery Office Ltd., London, UK, 2013 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/211180/FuelPovFramework.pdf.

[27] T. Oreszczyn, I. Ridley, S.H. Hong, P. Wilkinson, Mould and winter indoor relative humidity in low income households in England, Indoor Built Environ. 15 (2006) 125–135, http://dx.doi.org/10.1177/1420326X06063051.

[28] N. Shortt, J. Rugkåsa, J. Rugkasa, The walls were so damp and cold fuel poverty and ill health in Northern Ireland: results from a housing intervention, Health Place 13 (2007) 99–110, http://dx.doi.org/10.1016/j.healthplace.2005.10.004.

[29] J. Gilbertson, M. Stevens, B. Stiell, N. Thorogood, Home is where the hearth is: grant recipients' views of england's home energy efficiency scheme (Warm front), Soc. Sci. Med. 63 (2006) 946–956, http://dx.doi.org/10.1016/j.socscimed.2006.02.021.

[30] S.H. Hong, J. Gilbertson, T. Oreszczyn, G. Green, I. Ridley, A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment, Build. Environ. 44 (2009) 1228–1236, http://dx.doi.org/10.1016/j.buildenv.2008.09.003.

[31] J. Rosenow, Energy savings obligations in the UK—A history of change, Energy Policy 49 (2012) 373–382, http://dx.doi.org/10.1016/j.enpol.2012.06.052.

[32] OFGEM, Energy Companies Obligation (ECO): Guidance for Suppliers, OFGEM, London, UK, 2013. http://www.ofgem.gov.uk/Sustainability/Environment/ECO/guidance/Documents1/EnergyCompanies Obligation (ECO)Guidance for Suppliers – 15 March.pdf.

[33] DECC, Process Evaluation of the Warm Front Scheme, Department of Energy and Climate Change, London, UK, 2014. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/322901/Warm_Front_Evaluation_Report.pdf.